Advancements in the IR PowerWorks Employing a Ceramic Turbine Rotor

IGTI Microturbine Session
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Ingersoll-Rand's **Ceramic** Microturbine (CMT) Plan

- Following a low risk development path that will yield significant performance increase for PowerWorks™ products in 2003
  - Introduce ceramic turbine rotor to operate within proven limits of today's technology
    - Size and manufacturing limits
    - Temperature
    - Stress
  - Use metallic alloy for turbine housing and down-stream section, including recuperator.

70 kWe PowerWorks™ Microturbine Cogen System

PowerWorks 70kW Specifications

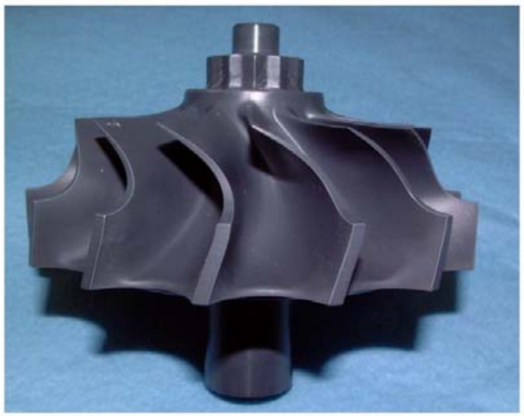
- 70kWe model
- Has 130% peaking power capacity on cold days (92 kWe)
- Electrical efficiency 29% LHV at ISO
- Low emissions with natural gas
- NOx < 4 ppmv, CO<9 ppmv@ 15% O2
- 80,000 hour engine life
- Grid-parallel or grid-isolated electrical generation
- Closed transitions to grid-isolated mode during grid outages
- Automatic block load handling up to 70kW

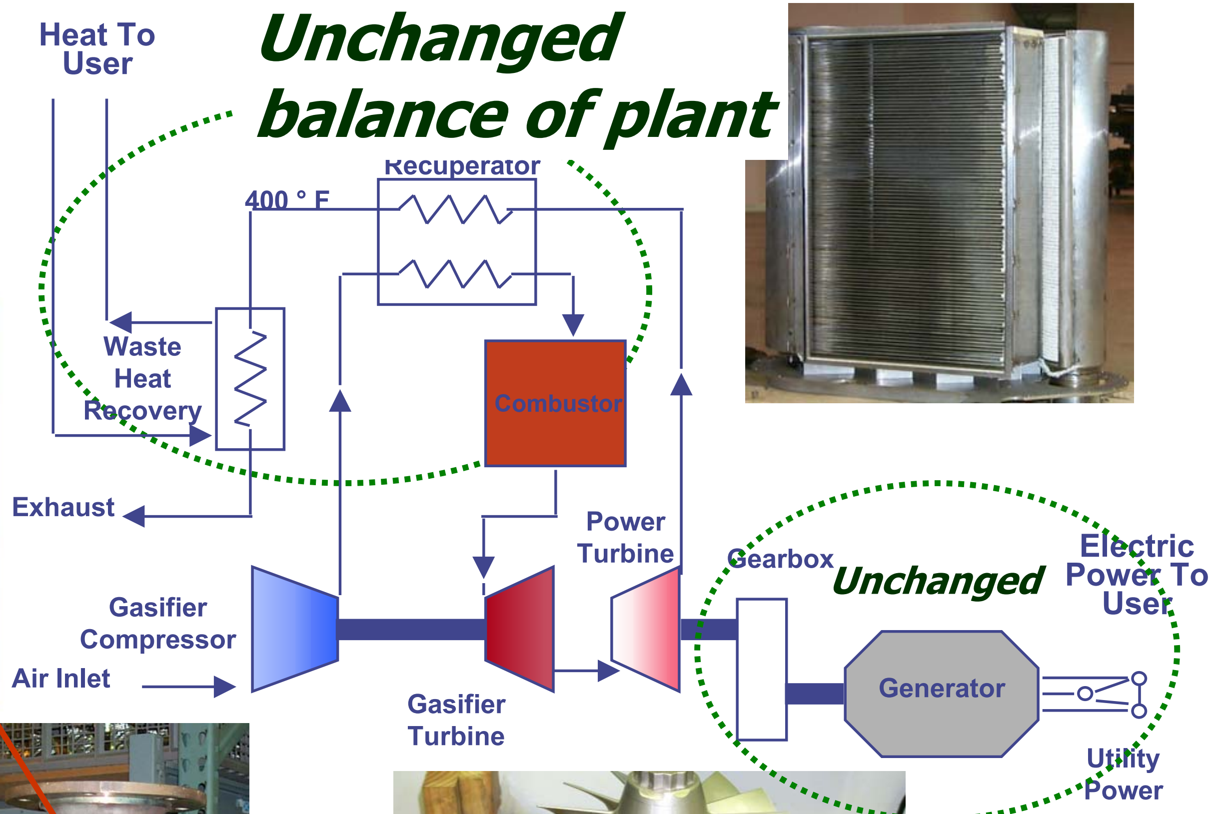
Trade Study Final Conclusions:

- Define cycle to utilize low-cost stainless steel recuperator
  - Gas inlet temperature below 700 C
  - Moderate turbine inlet temperature (TIT) (1000 to 1020 C) - to avoid unacceptable recession and coating cost/complexity
  - Resulting rise in pressure ratio to 4.8 to 5.2
- Low ceramic rotor tip speed - (Expansion ratio ~ 2 to 2.2)
  - show large margin based on stress predictions, leading to low statistical failure predictions
- Build from Kyocera's proven manufacturing base
  - Adopt experience form high volume turbocharger manufacturing - not the more developmental and expensive ceramics
  - Keep rotor diameters below about 100-mm

PowerWorks™ - Frame 3

Ceramic rotor

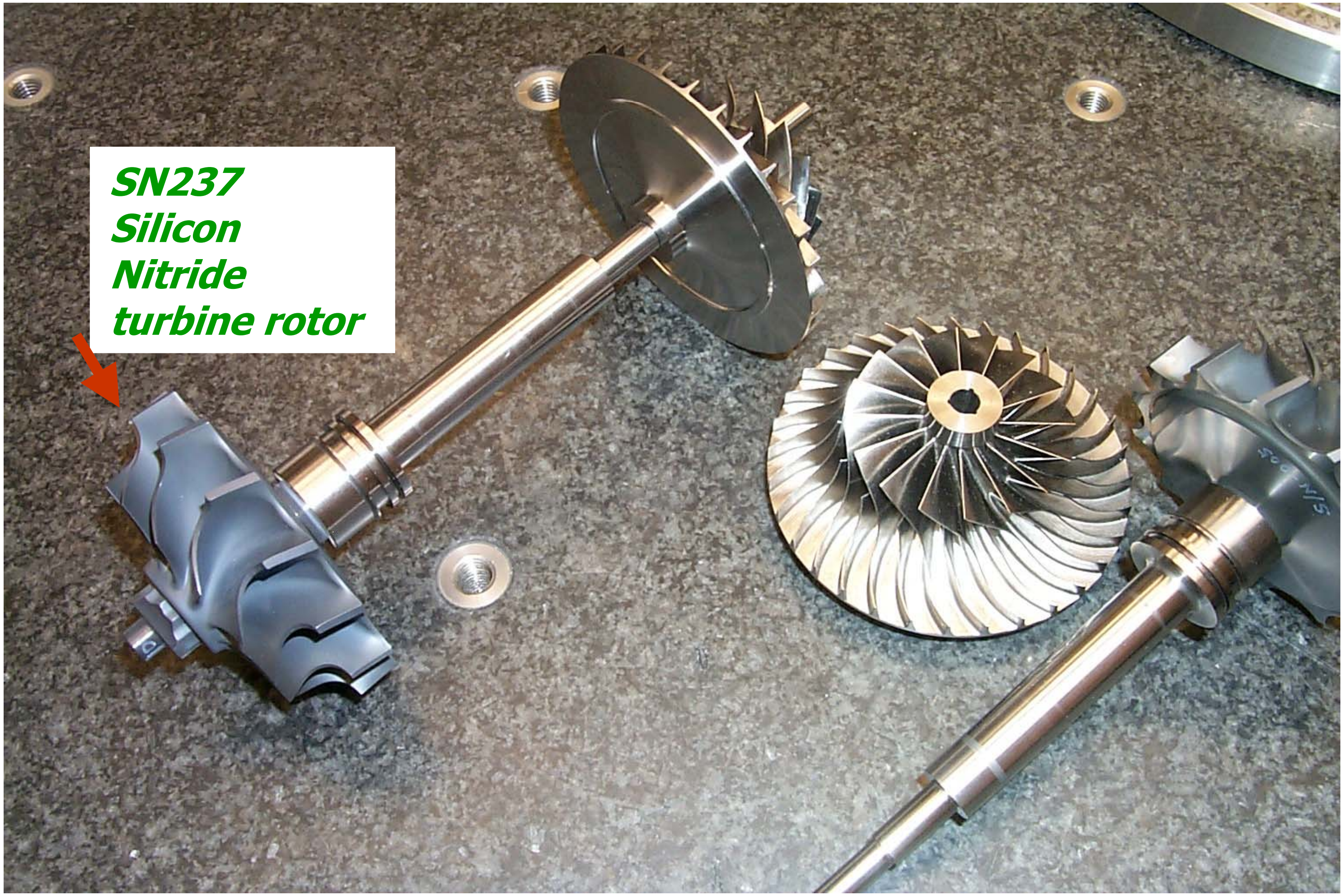




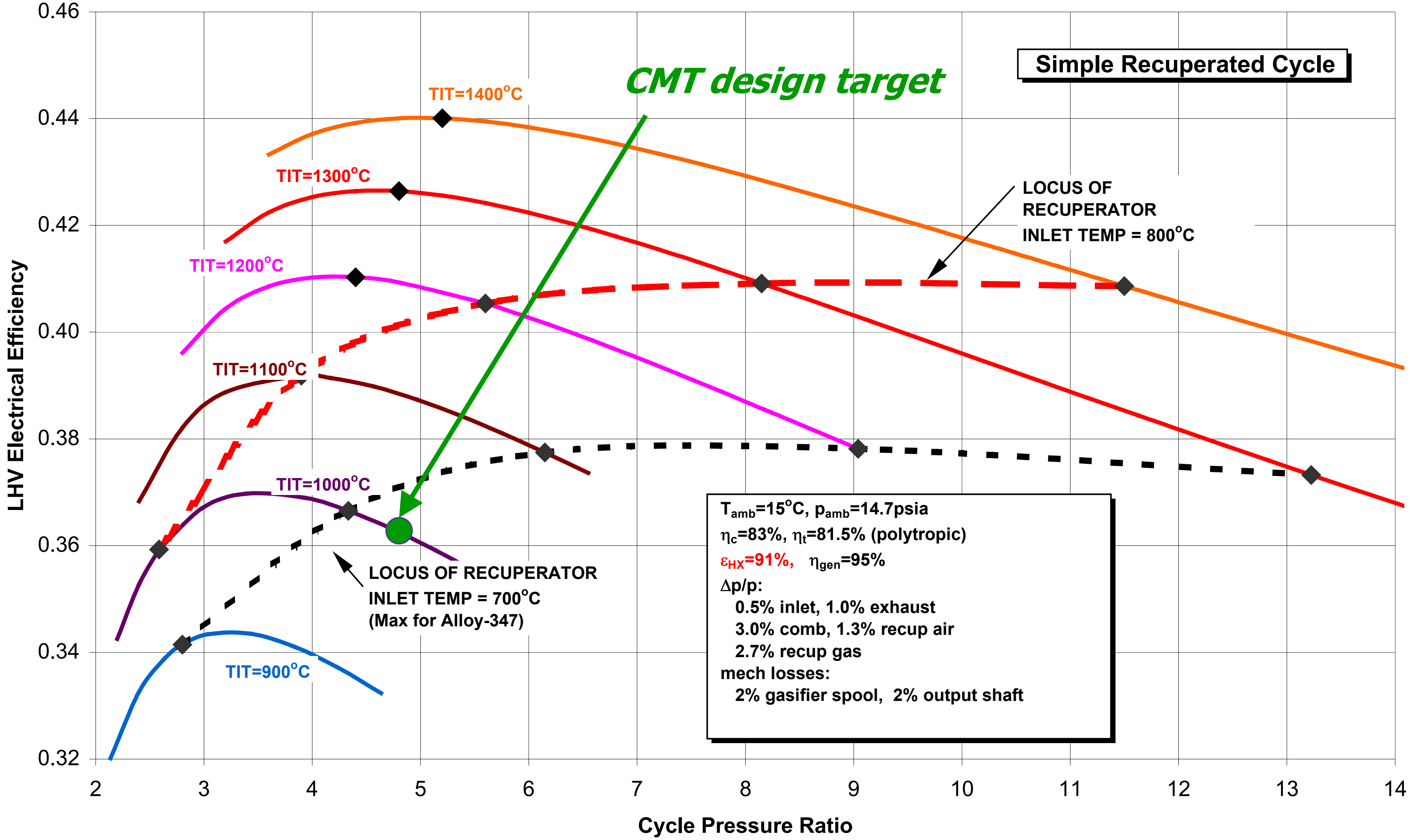
Metallic power turbine (IN713LC)

All new and improved aero-components (compressor + 2 turbines)

Turbine-compressor rotating group



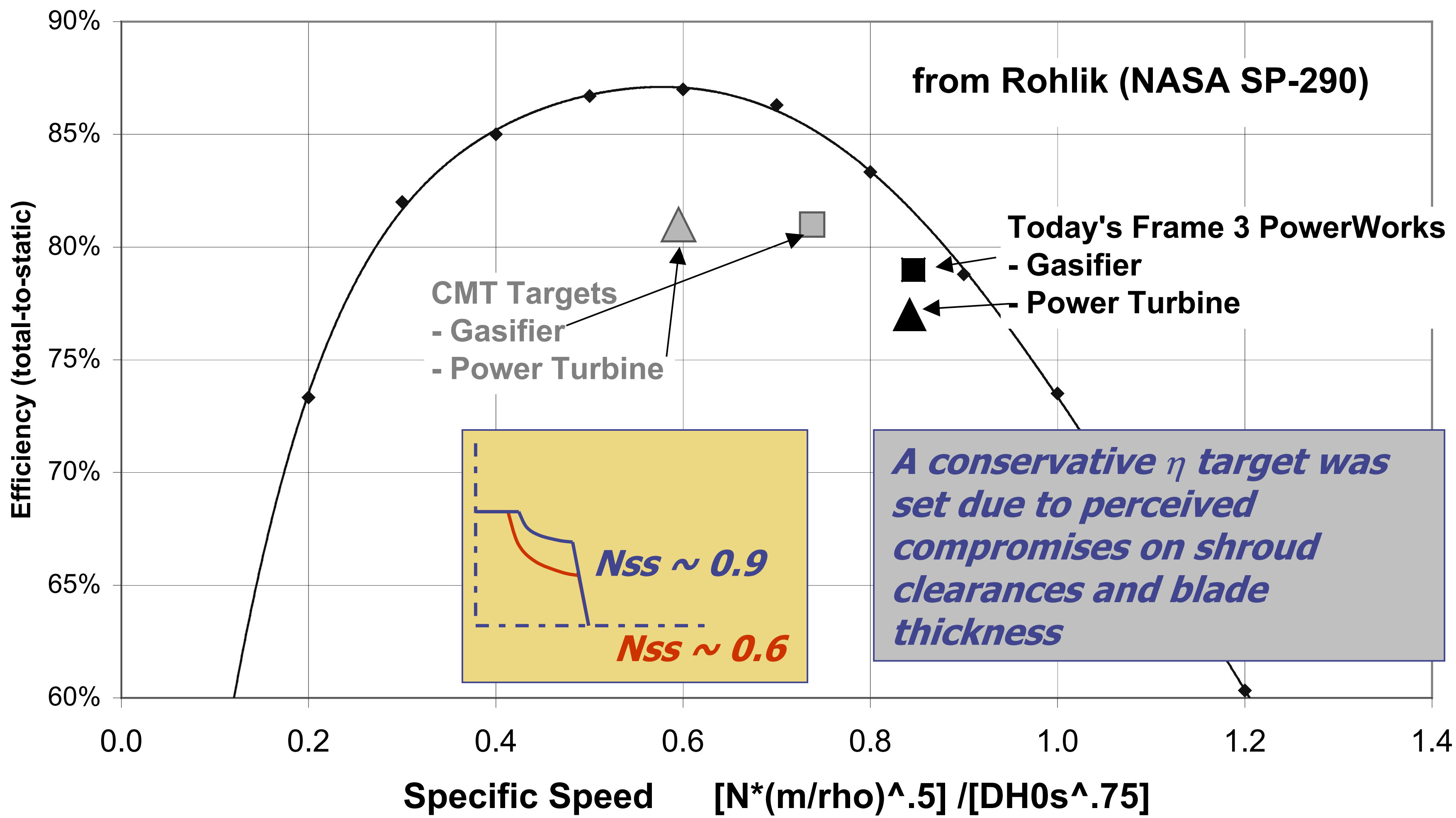
Cycle selection - Defining recuperator stainless alloy, sets options for PRc and TIT

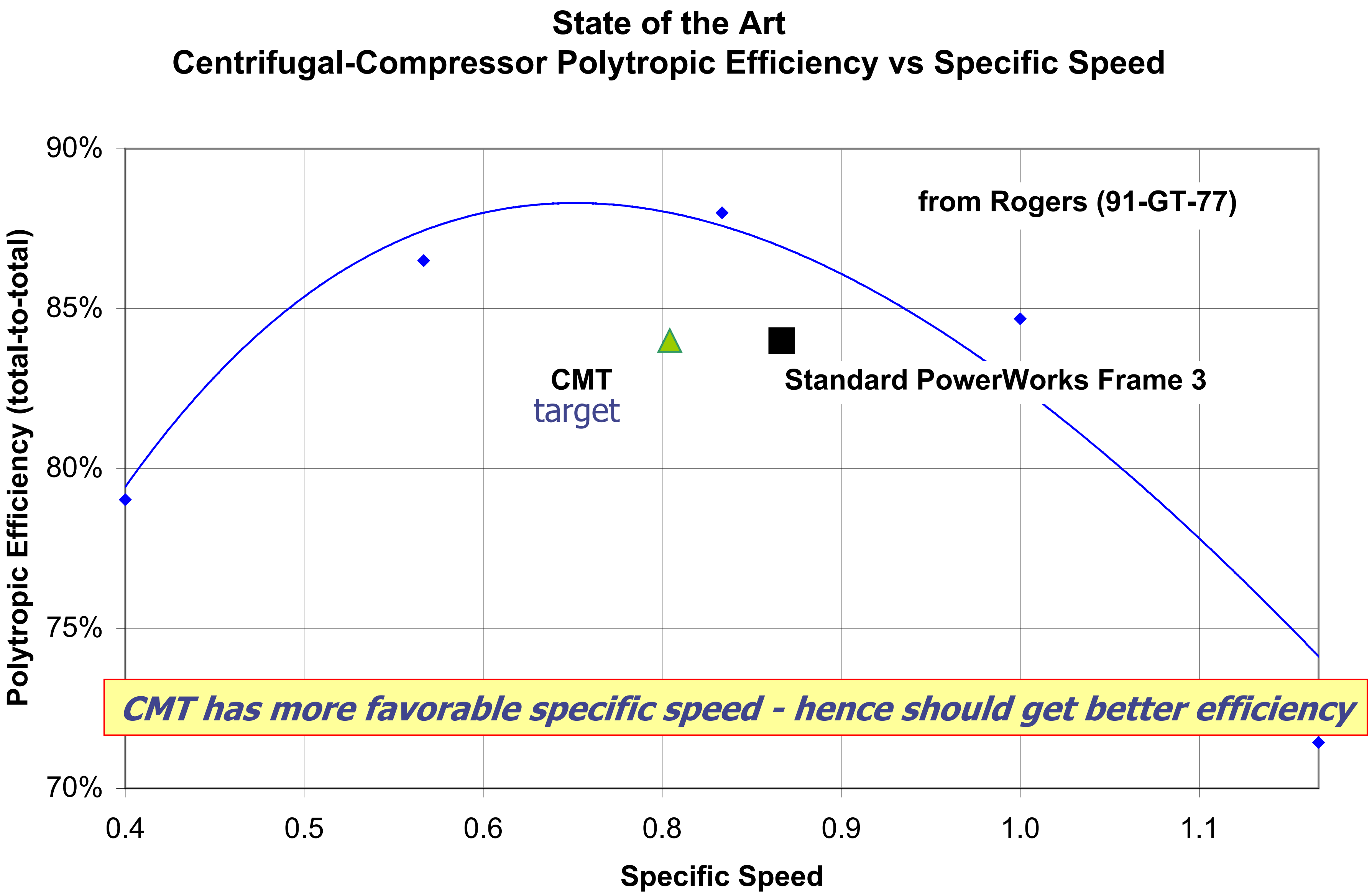


Performance optimization within proven and conservative limits of monolithic Silicon Nitride

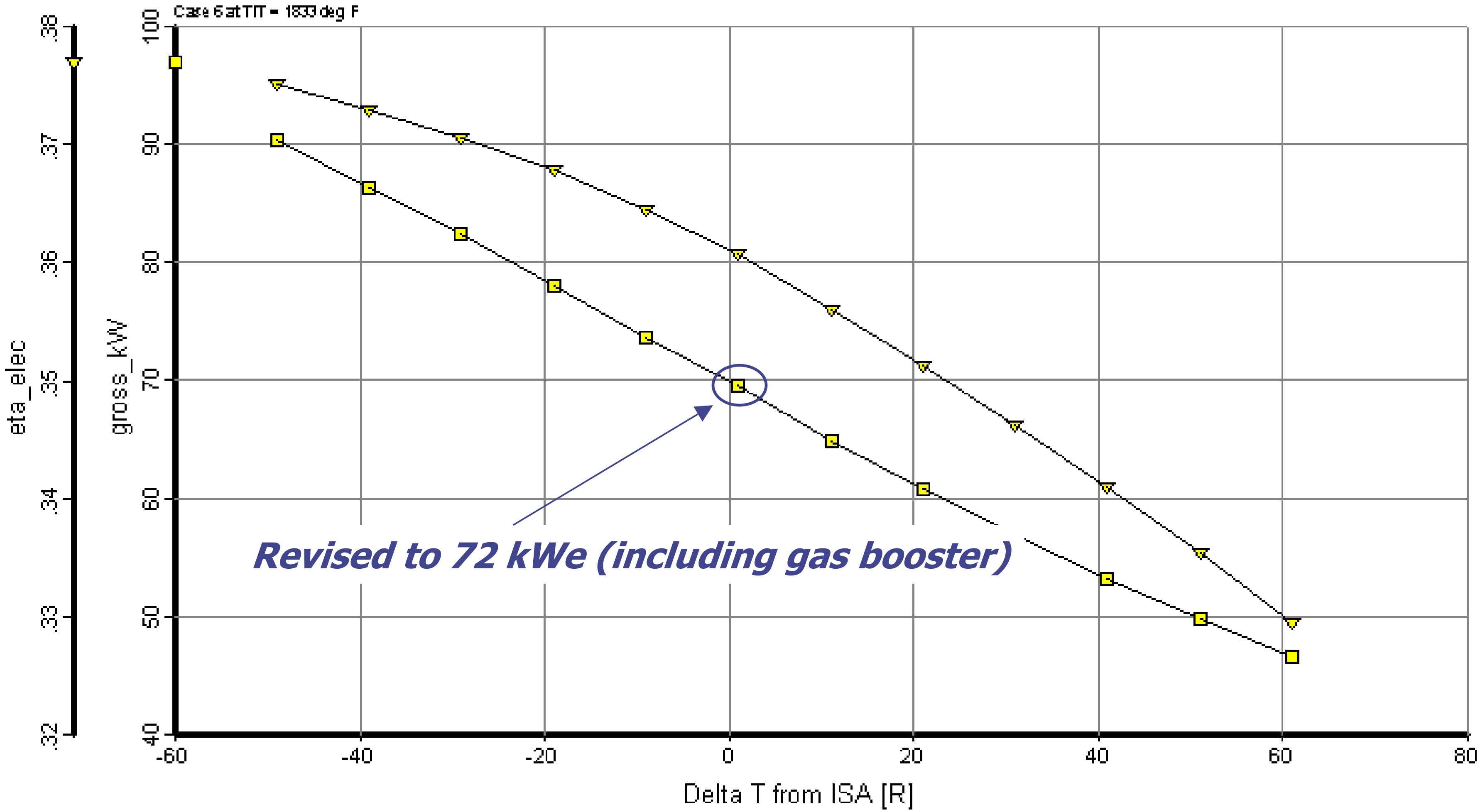
- Gasifier Turbine Aerodynamic and Thermodynamic Specifications
  - TIT = 1000 C
  - Expansion ratio = 2.1
  - Physical Speed = 97,500 RPM
  - Rotor tip speed = 485 m/s
  - Running clearance, inducer tip = 0.46 mm (0.018 in.)
  - Running clearance, exducer tip = 0.30 mm (0.012 in.)
  - Minimum blade thickness at inducer tip = 2 mm (0.080 in)
  - Minimum blade thickness at exducer trailing edge = 1.1 mm (0.044 in)
  - Nozzle-less turbine housing
  - Blade geometry must be “pullable” form mold
  - 100 mm rotor size limit

State of the art
Radial Inflow Turbine Efficiency vs Specific Speed




State of the Art
Centrifugal-Compressor Polytropic Efficiency vs Specific Speed
90%
85%
80%
75%
70%
Polytropic Efficiency (total-to-total)
0.4
0.5
0.6
0.8
0.9
1.0
1.1
Specific Speed
from Rogers (91-GT-77)
CMT
target
Standard PowerWorks Frame 3
CMT has more favorable specific speed - hence should get better efficiency

PowerWorks CMT :
Ambient Temp Effect on Power and Efficiency

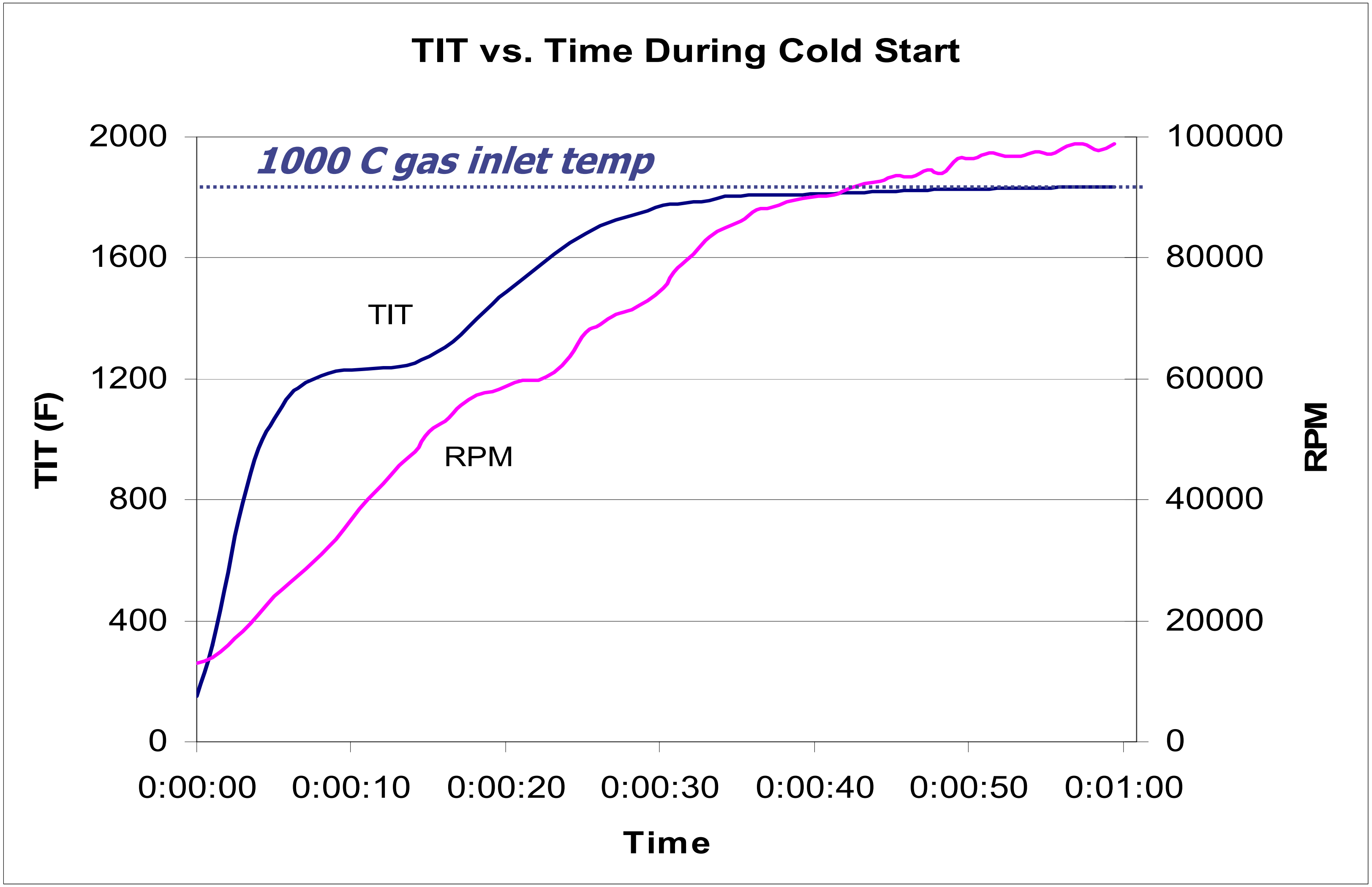


CMT Turbine Rotor Boundary Conditions for life analysis

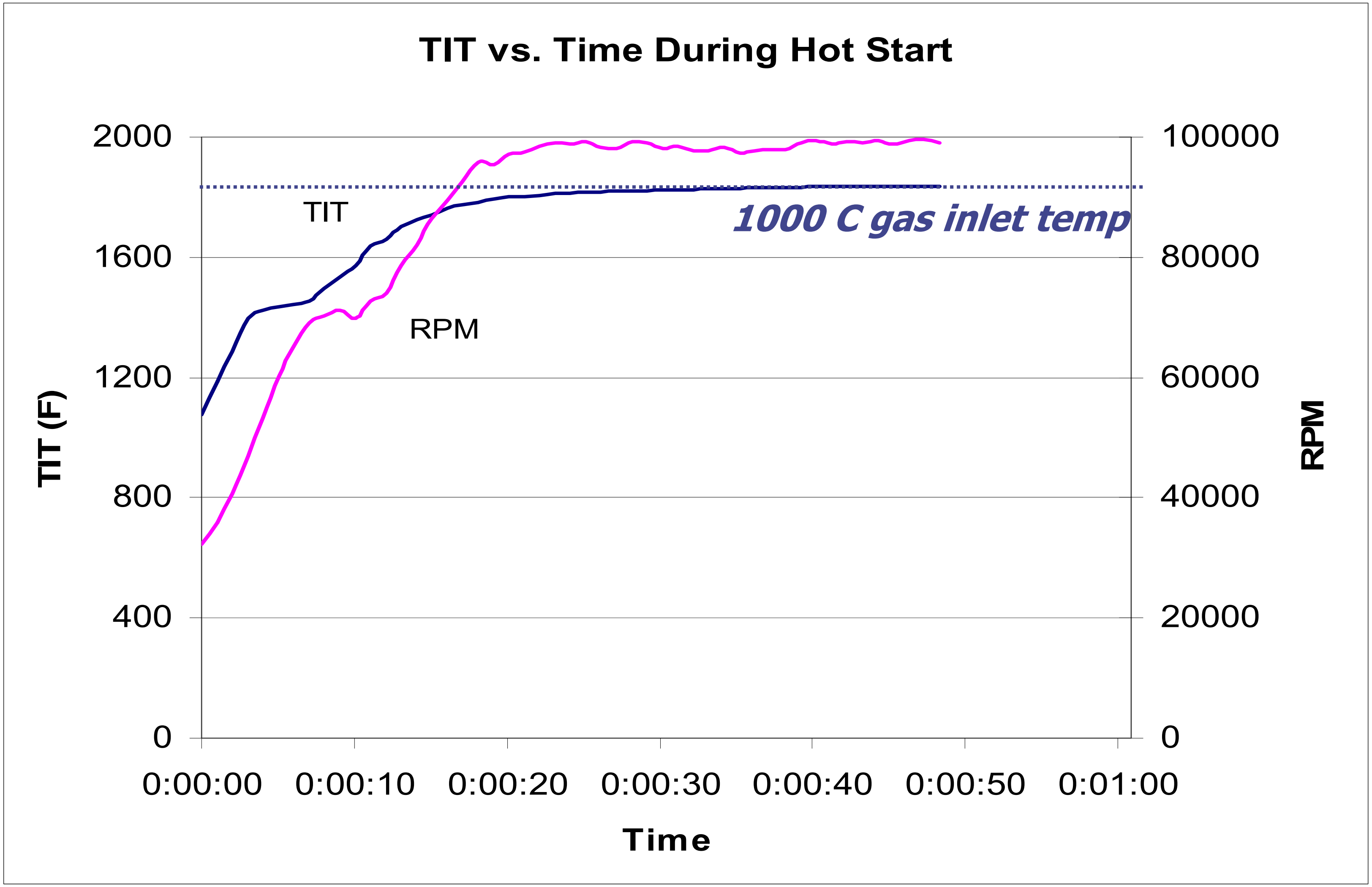
- Transient date derived from Frame 3 startup conditions
  - Hot and cold startup (transient) conditions derived form representative PowerWorks measurements.
  - Transient data scaled to CMT application:
    - Temperatures scaled from 870 C to 1000 C TIT
    - Speeds scaled from 72,000 to 97,500 RPM
    - Rate of acceleration scaled by the ratio of the inertias of the Frame 3 PowerWorks and the CMT rotor
- Steady state data derived from BANIG™ computer simulation

**** BANIG is a trademark of Concepts NREC***

CMT Rotor Cold Start



CMT Rotor Hot Start



CMT Rotor Heat Transfer Coefficients

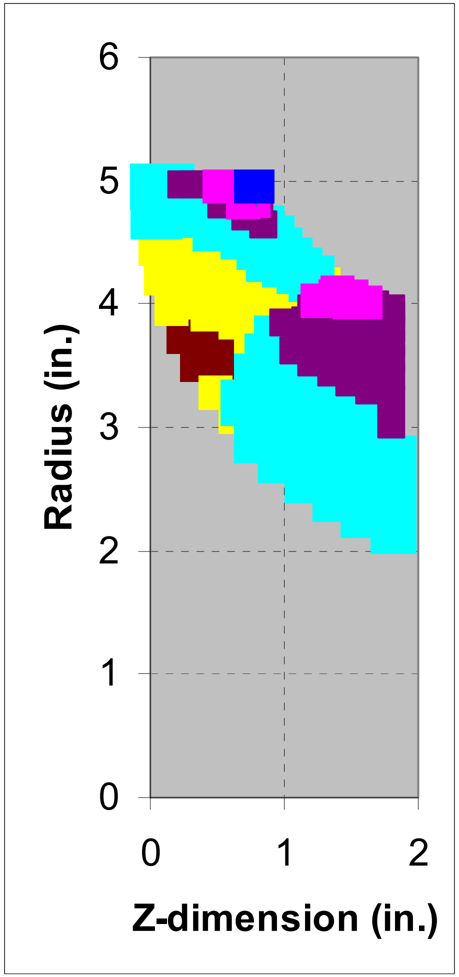
- Steady state heat transfer coefficients derived from computer simulation of rotor performance
- heat transfer coefficient calculated using:

$$\mathrm{Re} < 90{,}000:$$

$$Nu = 0.332 \cdot \mathrm{Re}^{1/2} \cdot \mathrm{Pr}^{1/3}$$

$$\mathrm{Re} > 90{,}000:$$

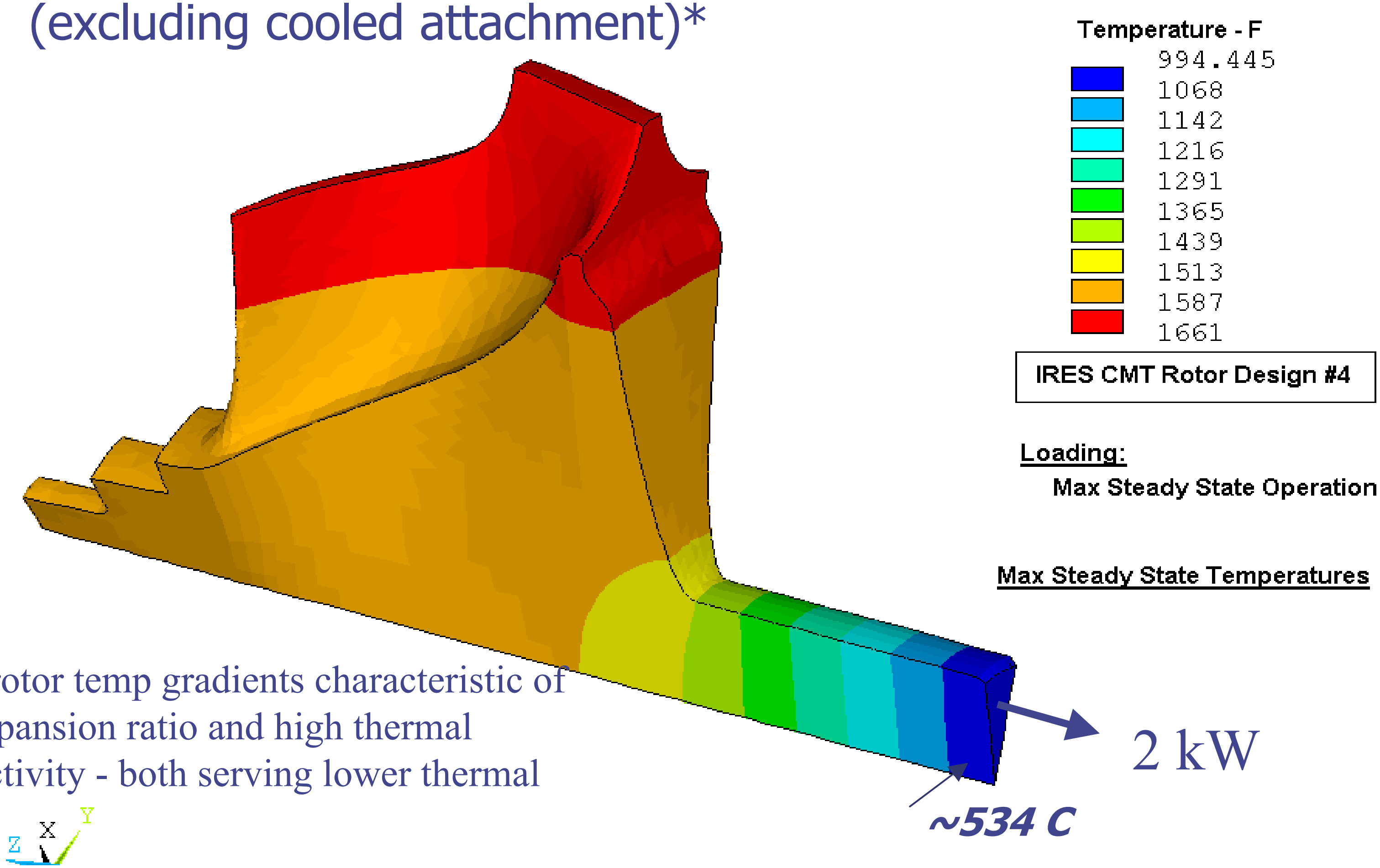
$$Nu = \frac{\frac{C_f}{2} \cdot \mathrm{Re} \cdot \mathrm{Pr}}{1 + (12.7 \cdot (C_f{}^{1/2} \cdot (\mathrm{Pr}^{2/3} - 1)))}$$



color	htc
	BTU/ft2F
MAROON	40
YELLOW	75
LTBLUE	125
PURPLE	175
PINK	210
DARKBLUE	305

CMT Rotor Steady State Temperatures

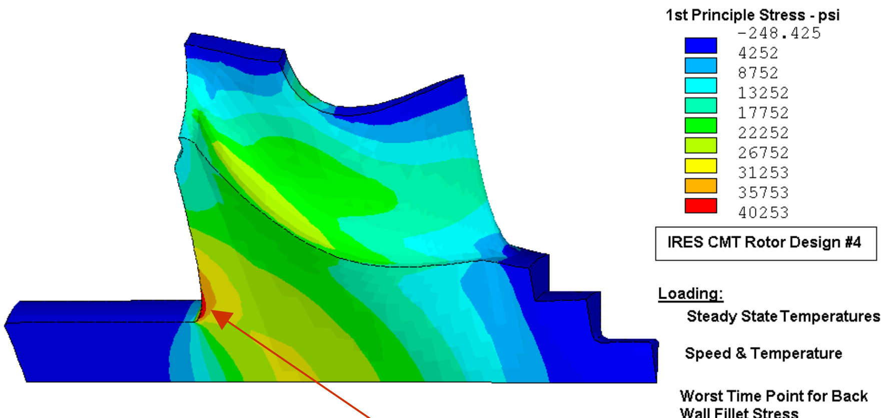
- TIT = 1000 C
- Maximum adiabatic Wall Temperature = 905 C
- Maximum rotor temperature difference = 60 C (excluding cooled attachment)*

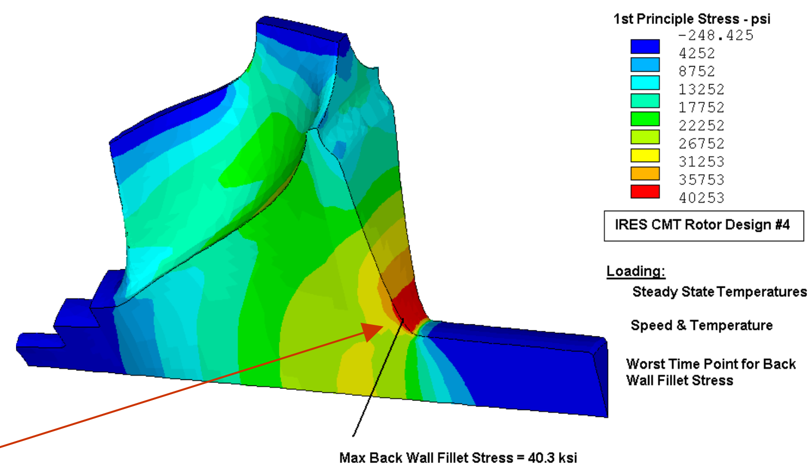


* low rotor temp gradients characteristic of low expansion ratio and high thermal conductivity - both serving lower thermal stress

CMT Rotor Steady-State Stresses (Principle)

- Kyocera stipulated design target of 200 MPa for SN237
- Steady state critical stress location is at back wall fillet
  - currently evaluating to 275 MPa (at bore)
  - can be further alleviated with larger fillet, if necessary



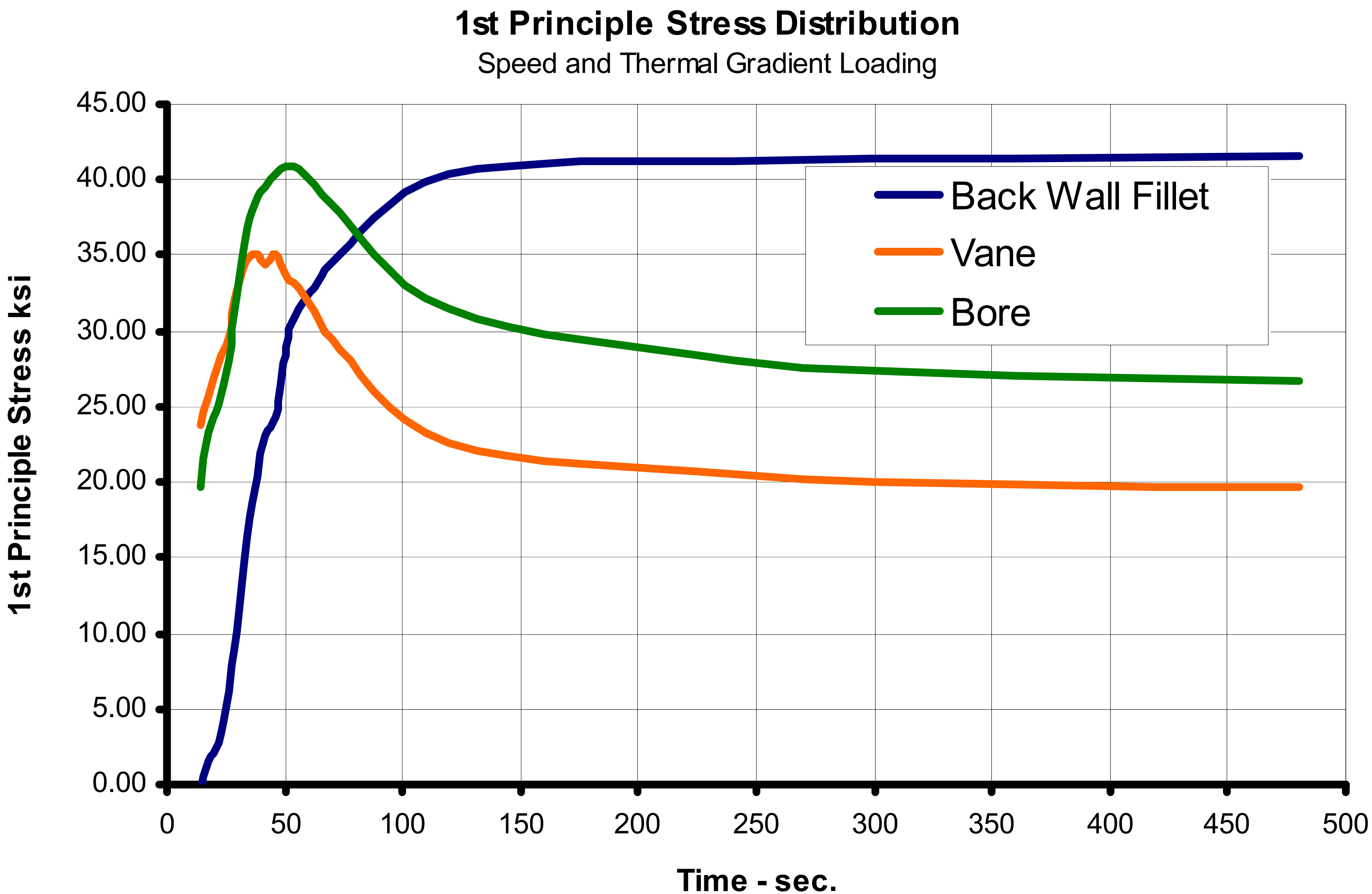


View #2

275 MPA

All blade and root is below 200 MPa

CMT Rotor Cold Start Stress Profiles



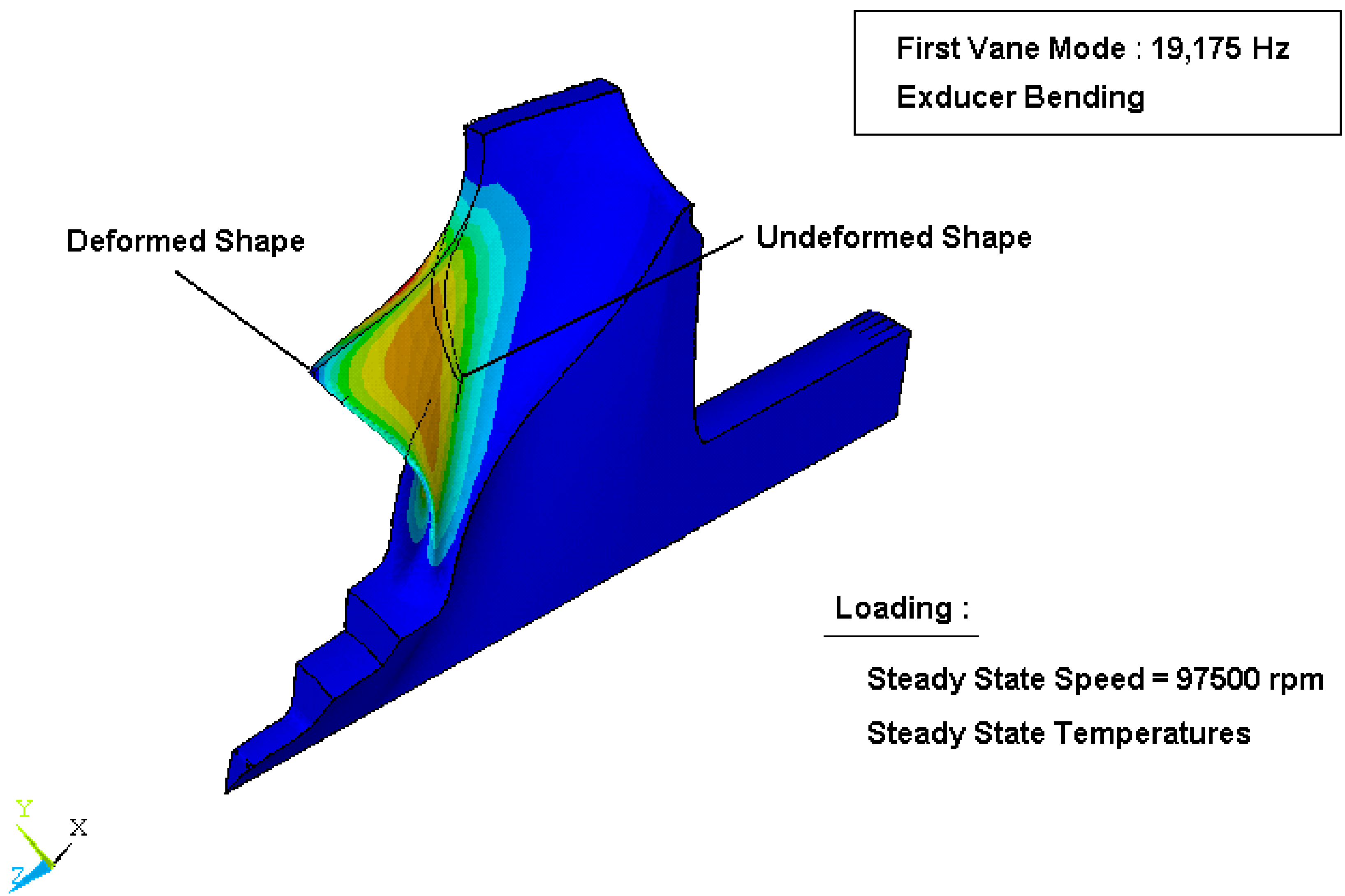


Fig 26. IRES, CMT Rotor Design #4, Dynamics Analysis Results.

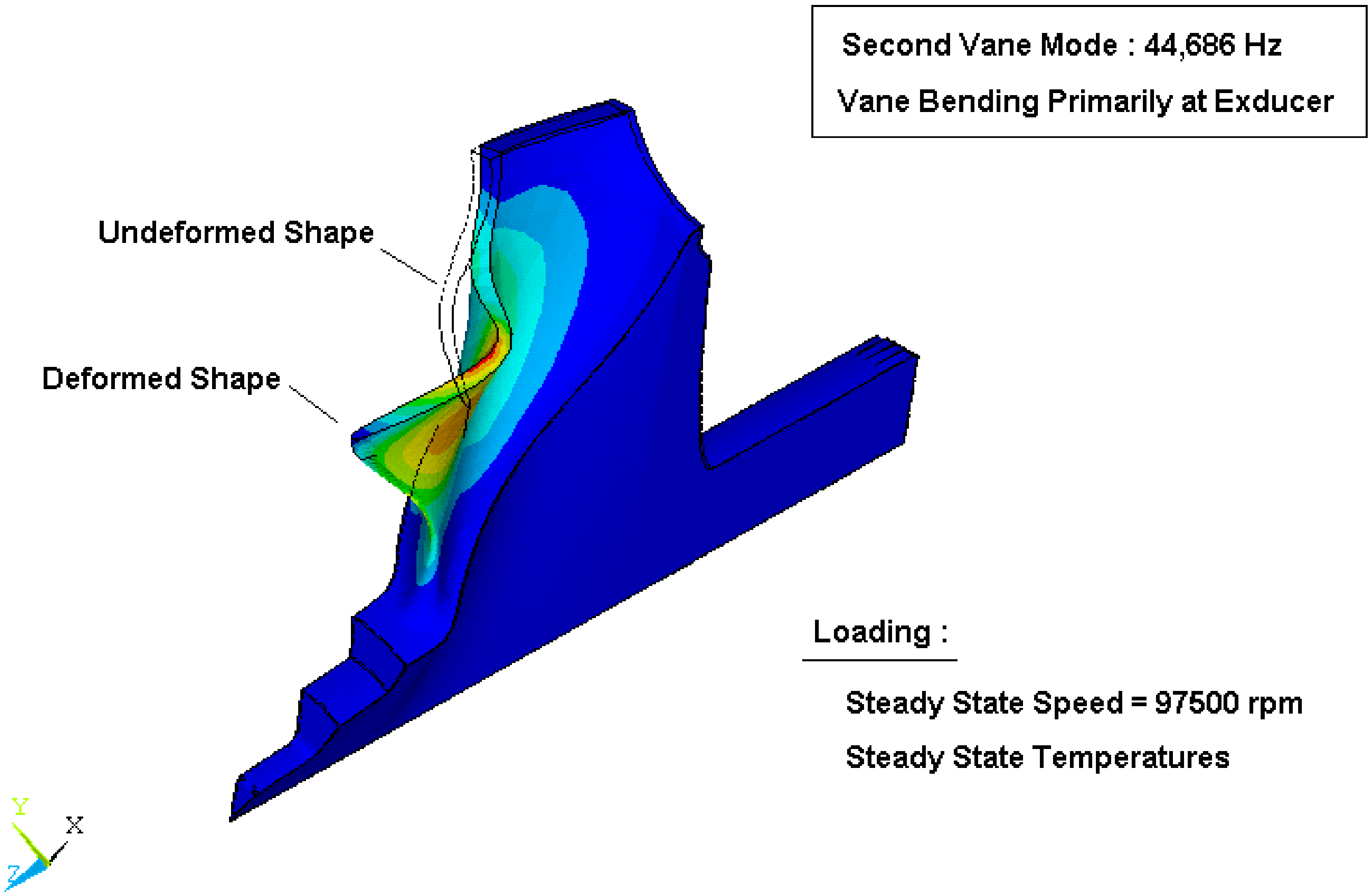
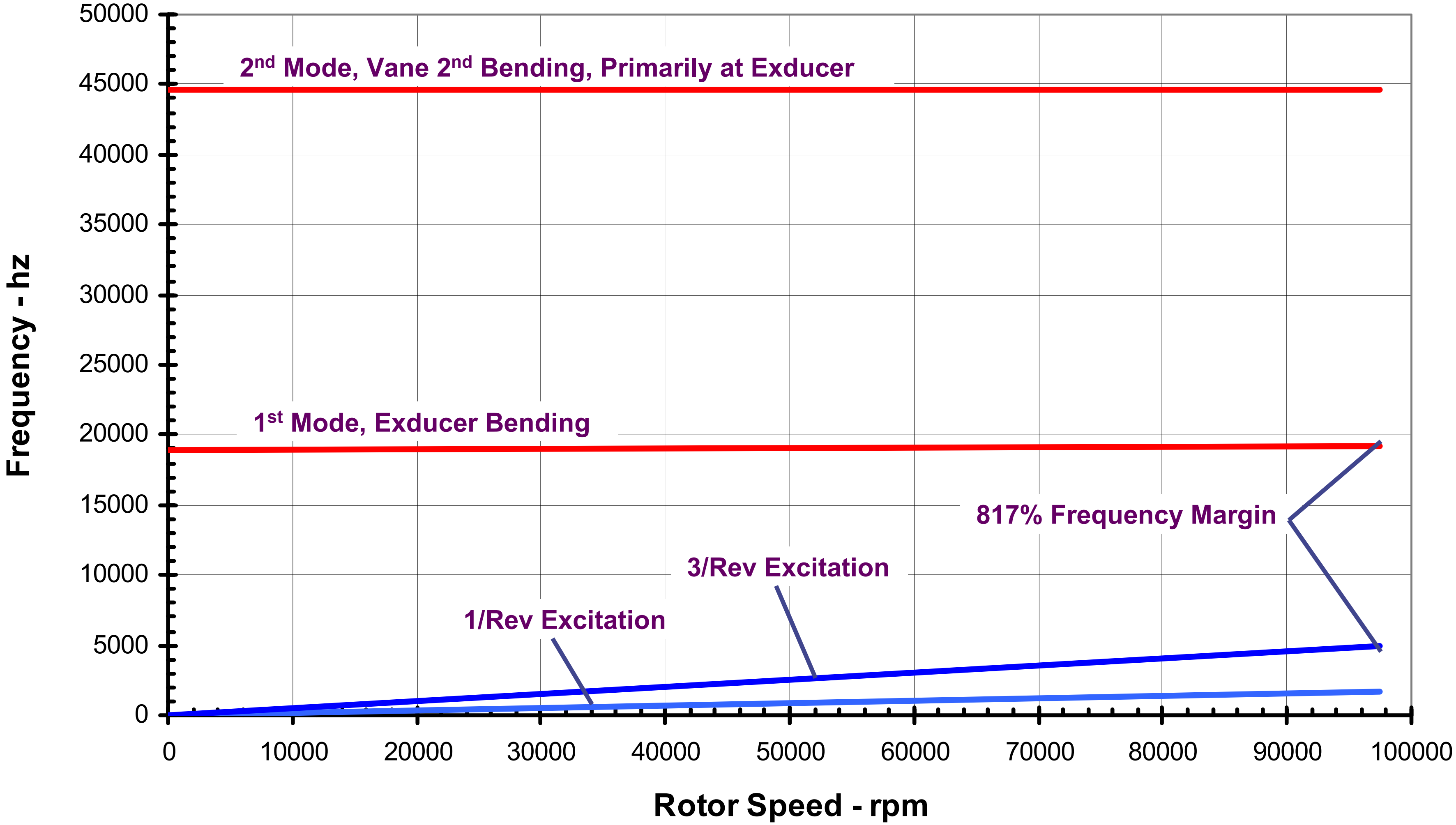


Fig 27. IRES, CMT Rotor Design #4, Dynamics Analysis Results.

IRES CMT Gasifier Rotor, Campbell Diagram



CARES Analysis based on ORNL Materials Data Base

Material	Data year	Manufacturer
SN282	2001	Kyocera
SN237	2001	Kyocera
AS800	1995	Honeywell (Formerly Allied Signal
NT154	1989	St. Gobain (formally Norton)

CARES Model Results

SN 237 - 2001 Vintage Material

	Steady State		38 Seconds		54 Seconds	
Probability of Failure	0.000000000747451		0.000001514190000		0.000001025080000	
Reliability	0.999999999252549	(9 nines)	0.999998485810000	(5 nines)	0.999998974920000	(5 nines)
Failure Rate	1337880343		660419		975534	

SN 282 - 2001 Vintage Material

	Steady State		38 Seconds		54 Seconds	
Probability of Failure	0.000000032730000		0.000075857000000		0.000034566800000	
Reliability	0.999999967270000	(7 nines)	0.999924143000000	(4 nines)	0.999965433200000	(4 nines)
Failure Rate	30553009		13183		28929	

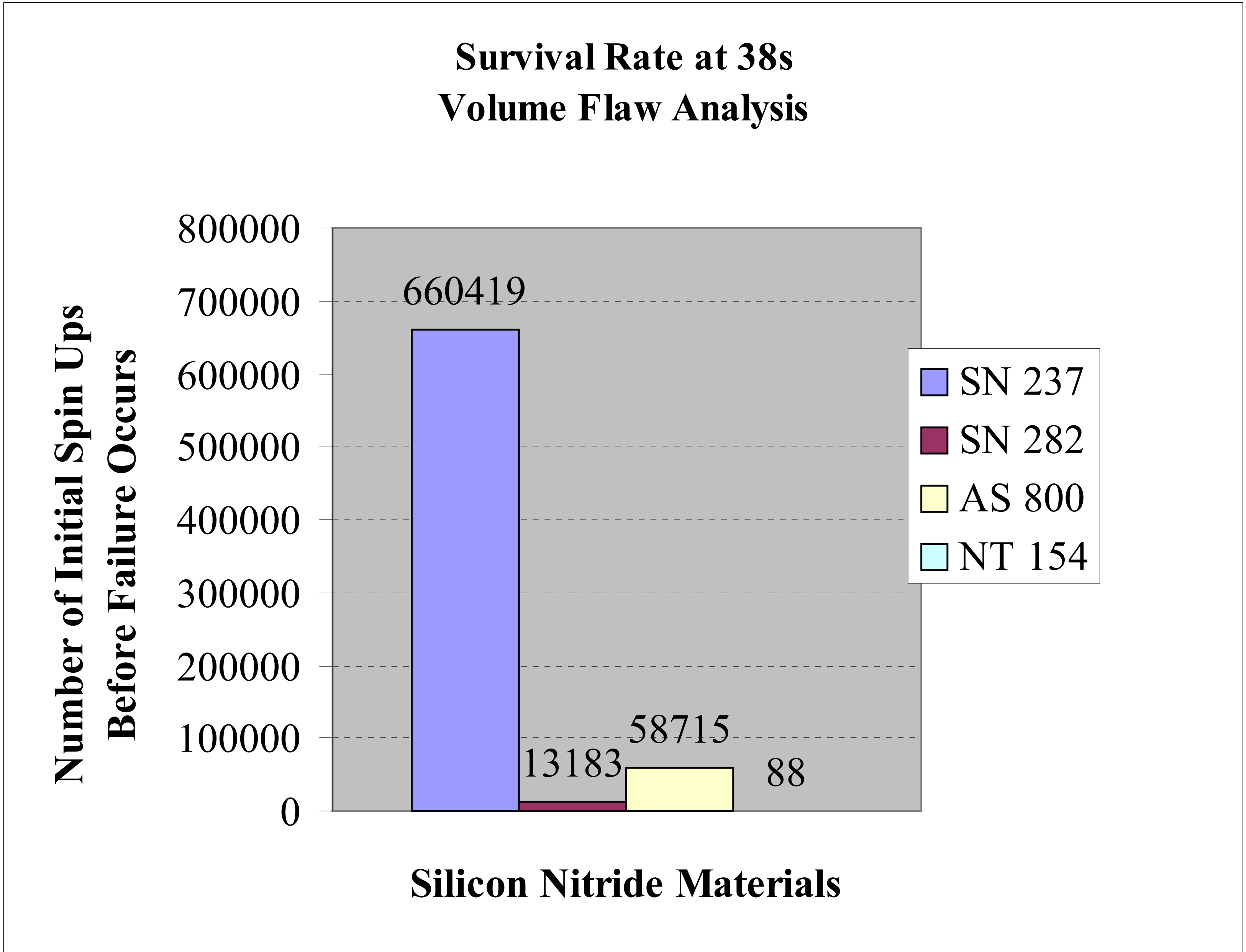
AS 800 - 1995 Vintage Material

	Steady State		38 Seconds		54 Seconds	
Probability of Failure	0.000000021028900		0.000017031300000		0.000008595400000	
Reliability	0.999999978971100	(7 nines)	0.999982968700000	(4 nines)	0.999991404600000	(5 nines)
Failure Rate	47553605		58715		116341	

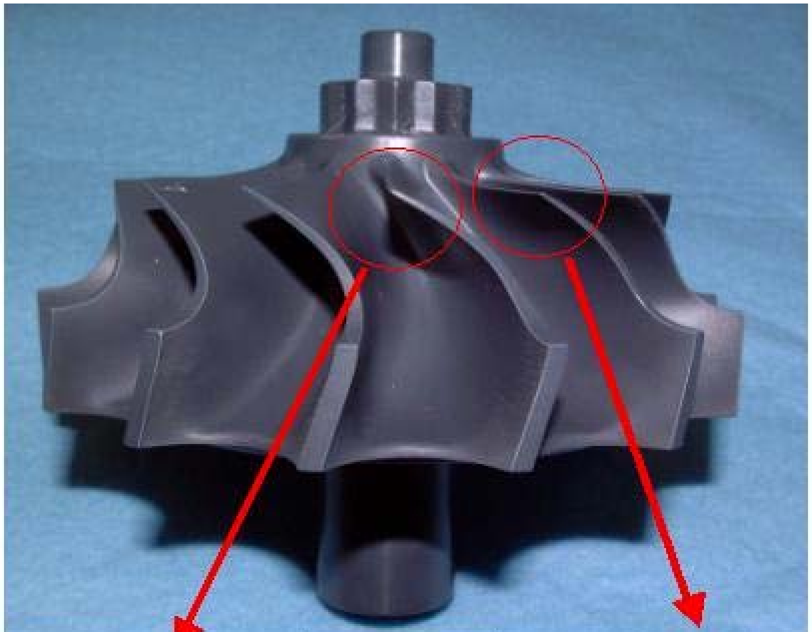
NT 154 - 1989 Vintage Material

	Steady State		38 Seconds		54 Seconds	
Probability of Failure	0.000237266000000		0.011407100000000		0.008427090000000	
Reliability	0.999762734000000	(3 nines)	0.988592900000000	(1 nine)	0.991572910000000	(2 nines)
Failure Rate	4215		88		119	

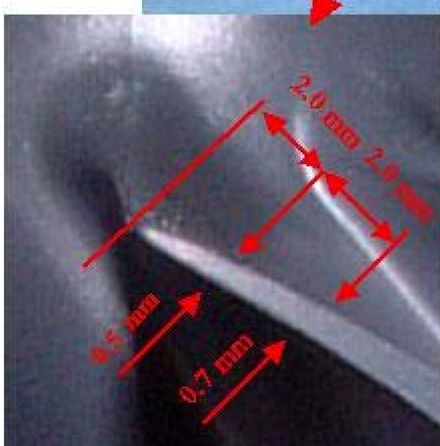
Notes from Steve Duffy:
- ***38 second condition appears to be worst case***


Survival Rate at 38s
Volume Flaw Analysis
Number of Initial Spin Ups Before Failure Occurs
800000
700000
600000
500000
400000
300000
200000
100000
0
660419
13183
58715
88
SN 237
SN 282
AS 800
NT 154
Silicon Nitride Materials

First Kyocera SN237 rotors fabricated for IR CMT Program (12/02)

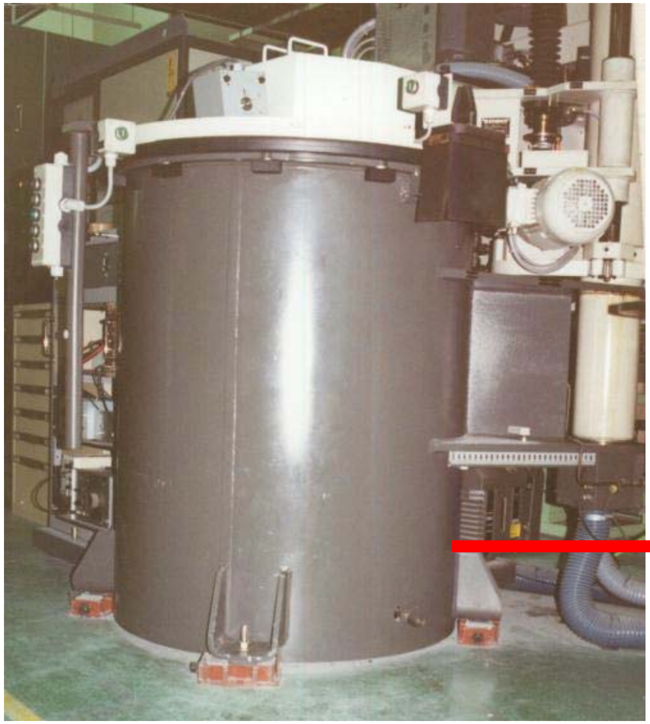


- Excellent blade true position and blade profile dimensional control
- Excellent surface finish
- Coordinate generation error resulted in ultra-thin blades

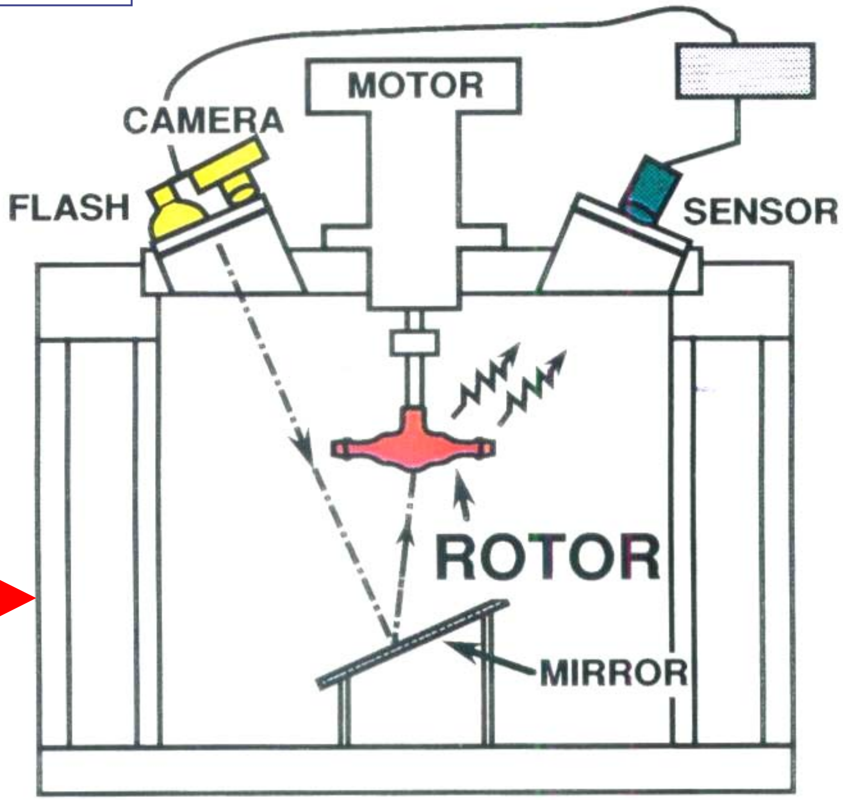


Evaluation Development

Cold Spin Test



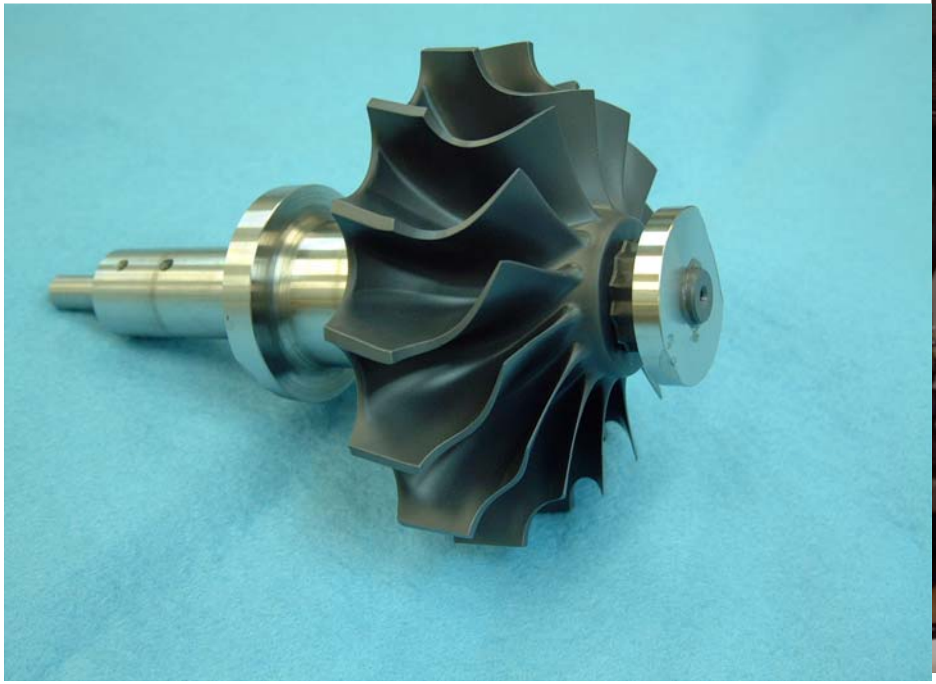
Cold spin test equipment

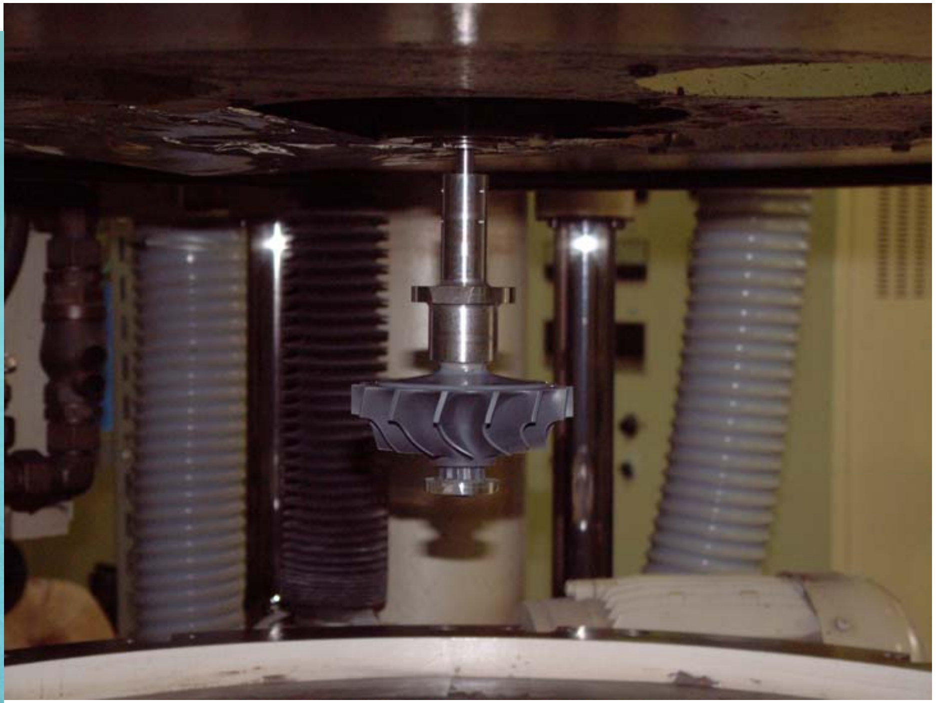


Cold spin system

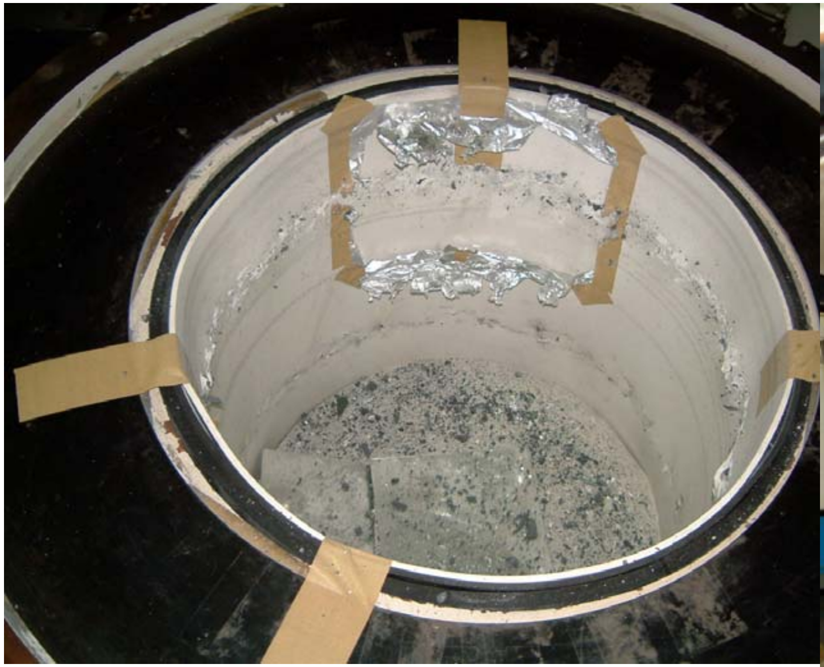
Evaluation Development

Cold Spin Test

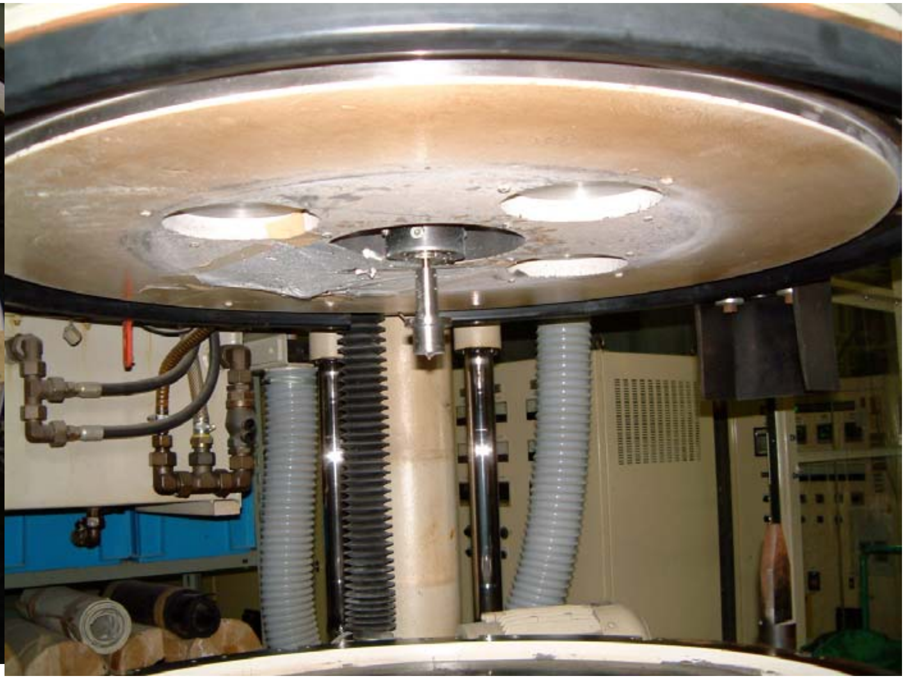




Spin pit after rotor burst at 167,197 RPM



SN237 rotor fragments



Rotor-less spindle

Cold Spin Test Results

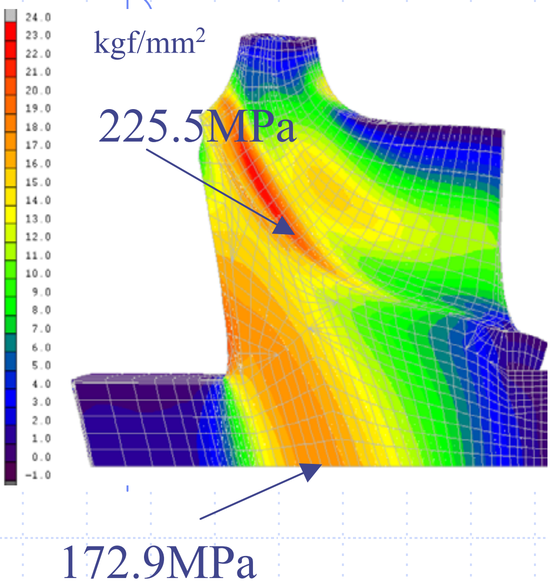
Room temperature, Material :SN237

Design Speed :97,500rpm

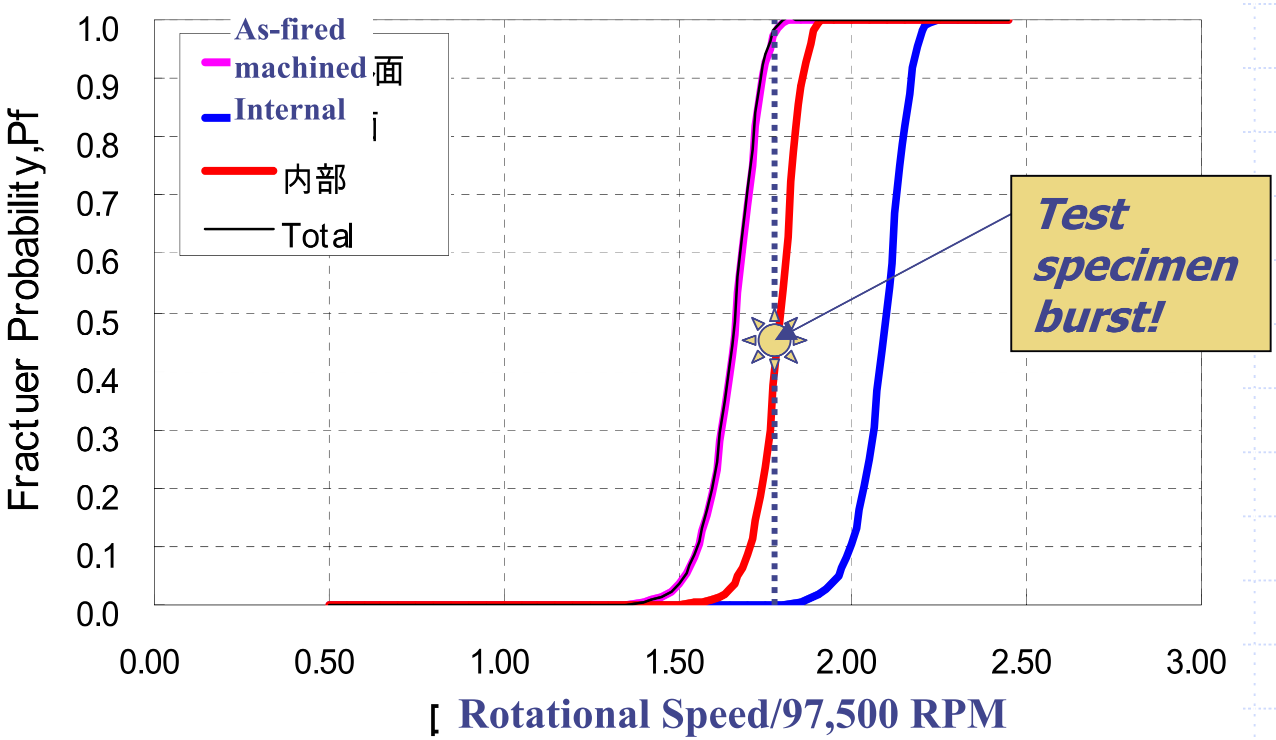
Burst Speed = 167,197 (sample #1, only sample)

Burst Speed ratio = 171% (Burst/Design)

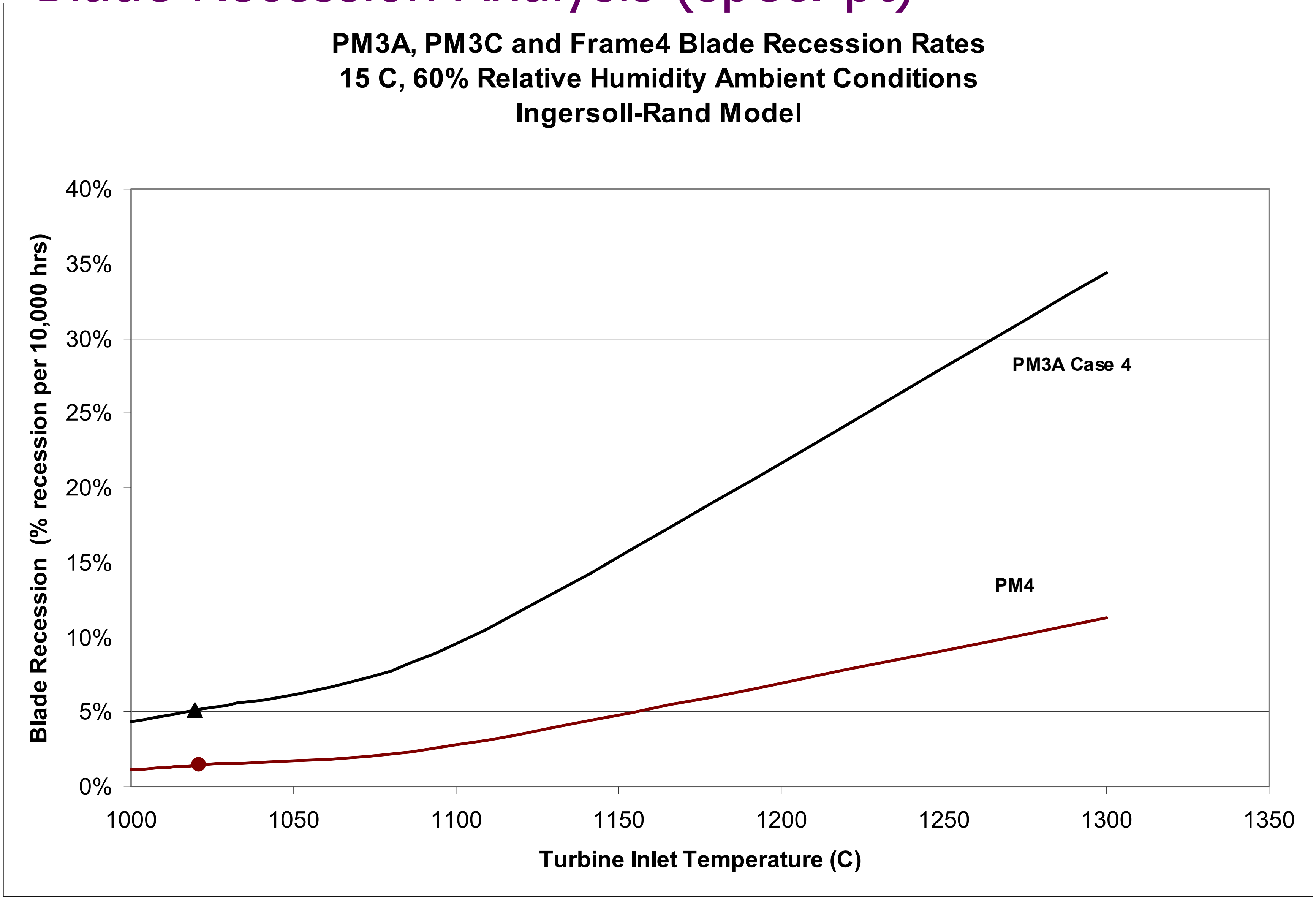
Burst Stress factor (N^2) = 2.9



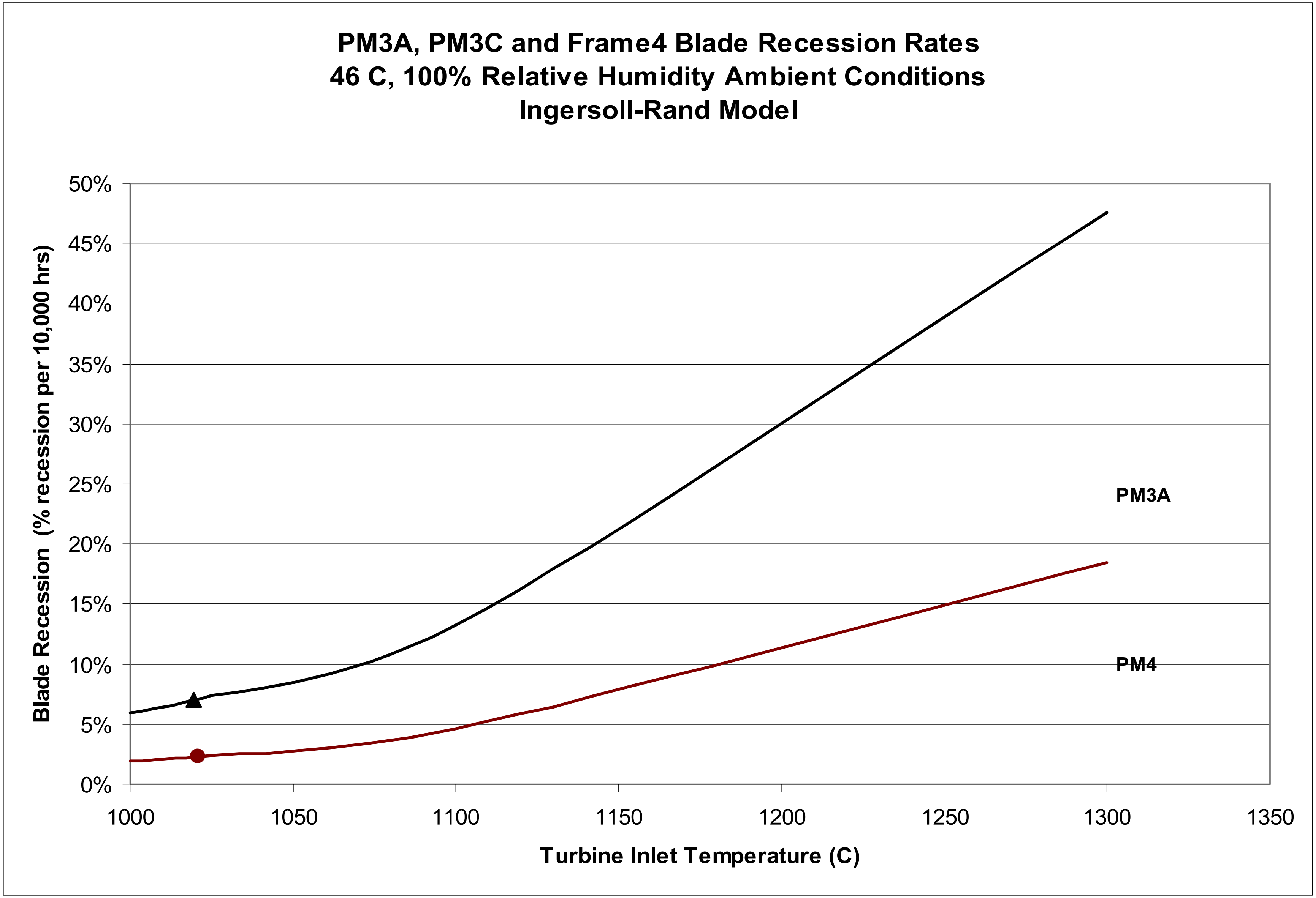
Fracture Probability of Rotor(SN237)

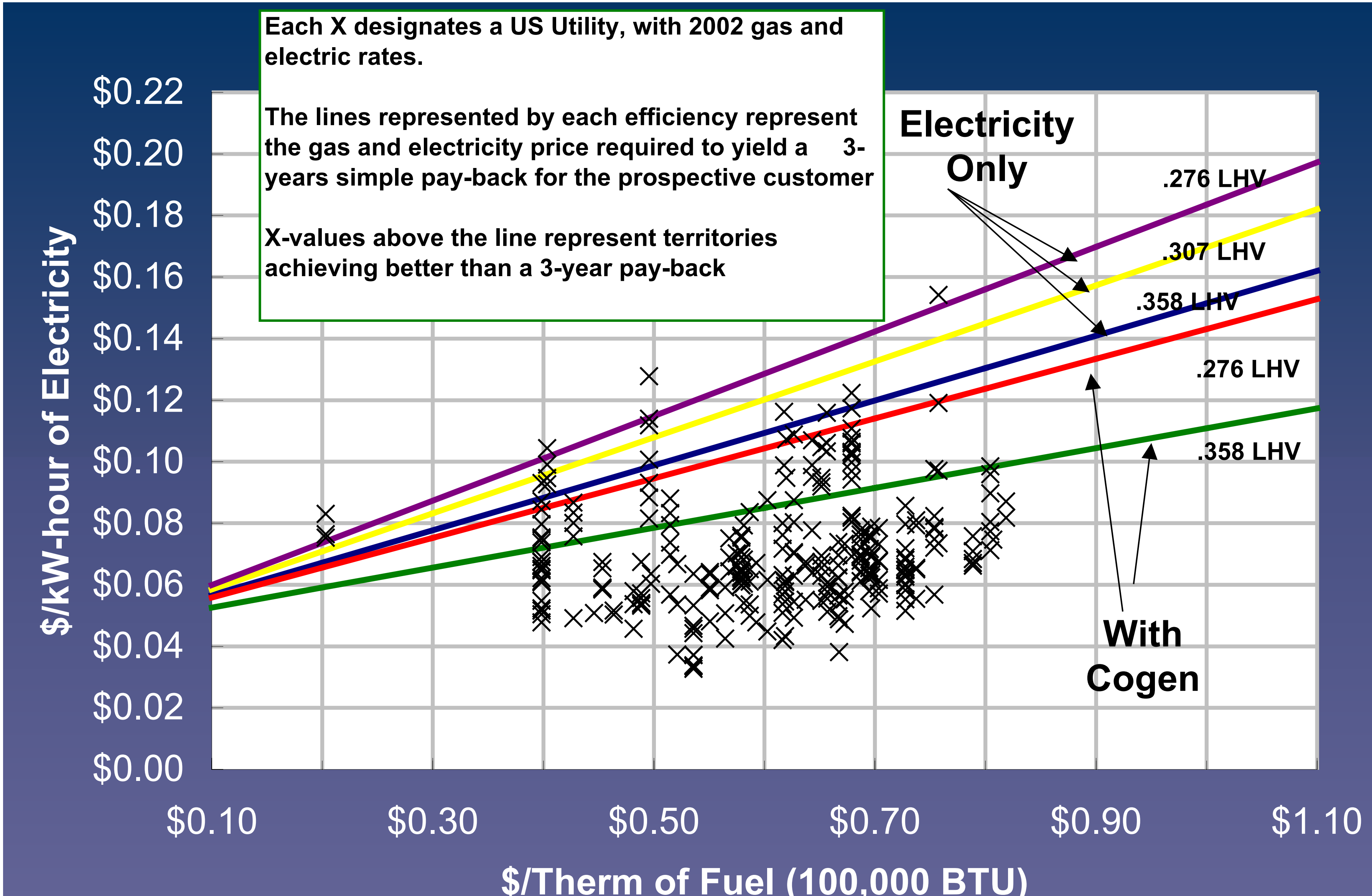


Blade Recession Analysis (spec. pt)



Blade Recession Analysis (worst case)





The improved efficiency of our "CMT " will increase the addressable market ten fold